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Effect of Upstream Reflector on Jet Screech

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Experimental studies were carried out to investigate the effect of an upstream reflector on underexpanded circular sonic jet screech. It is found that the feedback path and receptivity of the screech is controlled by the standing wave formed by the reflection of the sound wave from the reflector. The results also show that the jet can support more than one mode of screech (symmetric and helical or both helical) at a particular Mach number depending on the standing wave (excitation) wavelength. The variation of the screech wavelength λ_s with respect to the reflector distance exhibits a sawtooth pattern. In the single mode case the period between jumps in the sawtooth pattern is equivalent to the standing wave wavelength $\lambda_r/2$. When two modes exist, the interval of repetition of a particular mode is the wavelength of the standing wave. The mode, wavelength, and amplitude of the screech were affected by the size and position of the reflector. The Helmholtz number ($H_j = fD_j/a_j$) of the screech of a highly underexpanded jet is found to be constant, but the value of the constant depends on the screech mode ($H_j \approx 0.45$ for mode *C* and $H_j \approx 0.4$ for mode *D*).

Nomenclature

a_j	=	speed of sound of an equivalent correctly expanded jet
b	=	upstream distance from the nozzle lip to the reflector
D_e	=	internal diameter at the nozzle exit
D_j	=	diameter of an equivalent correctly expanded jet
f	=	frequency, Hz
H_j	=	Helmholtz number, fD_j/a_j
M_j	=	Mach number of an equivalent correctly expanded jet
St_j	=	Strouhal number, fD_j/U_j
U_j	=	velocity of an equivalent correctly expanded jet
λ_r	=	reference screech wavelength (wavelength of screech when the reflector is at the nozzle exit)
λ_s	=	screech wavelength

I. Introduction

An incorrectly expanded supersonic jet has shock associated noise in addition to turbulent mixing noise. Broadband shock associated noise and screech are the two components of the shock associated noise. Both of these noise components are generated by the interaction of a shock wave with an instability wave in the jet shear layer [1,2]. Unlike broadband shock associated noise, the screech tone is the result of a self sustained process which involves four steps [3–5]. These steps are 1) growth of the instability wave in the jet shear layer, 2) generation of sound by the interaction of the instability wave with the shock wave in the jet shear layer, 3) upstream propagation of sound (feedback), and 4) excitation of the instability wave in the initial shear layer of the jet by sound (receptivity). Out of these four steps the last two steps are not studied as deeply [6]. The details of the first two steps, which are common for both components of shock associated noise, are discussed in review papers by Tam [1,2].

The receptivity and feedback of the jet can be affected by the nozzle lip thickness and the presence of reflecting/absorbing objects surrounding the jet. Powell [3], who identified the screech tone, and Davis and Oldfield [7] noted that a reflective surface at or near the nozzle exit plane influences the screech significantly. Harper–Bourne and Fisher [8] studied the broadband shock associated noise by suppressing the screech tone using an acoustic foam covered reflector at the nozzle exit. Poldervaart et al. [9] were able to suppress/augment the screech by placing the reflective surfaces upstream and downstream of the nozzle exit. Ponton and Seiner [10] studied the effect of the nozzle lip thickness on underexpanded sonic jet screech. They showed that the lip thickness affects the screech mode and its amplitude. Kweon et al. [11] studied the effect of a reflector at the nozzle exit on the supersonic jet flow field. They concluded that for overexpanded jets, the reflector substantially increases the jet spreading rate and reduces the supersonic length of the jet, compared with moderately underexpanded jets.

Davis and Oldfield [7], Westley and Woolley [12], and Panda [13] found that the near field of the screeching jet contains a standing wave between the downstream propagating hydrodynamic pressure fluctuation in the jet and the upstream propagating acoustic wave. Norum [14] reported that the screech mode was affected by the presence of an upstream reflecting surface and nozzle exit conditions for a moderately underexpanded circular sonic jet. Nagel et al. [15] used an upstream reflector to cancel the jet screech in a moderately underexpanded circular sonic jet. They observed that when the reflector is located at odd multiples of $\lambda_r/4$ from the nozzle exit, the screech is minimized. They hypothesized that this suppression of the screech is due to the occurrence of a pressure minimum (node of the standing wave) at the nozzle exit. Similar studies were done by Raman et al. [6] using an annular reflecting surface upstream of the nozzle exit for rectangular underexpanded jets. They reported that the gap between the reflector and the nozzle can influence the cancellation effect. In addition to that, they concluded that the reflector affects the standing wave pattern, which in turn changes the receptivity of the jet. Recently, Nakazono et al. [16] reported that the effect of the reflector creates two kinds of standing waves in the near field of a screeching jet. One is the standing wave between the hydrodynamic pressure fluctuations in the jet (propagating downstream) and the screech pressure fluctuations (propagating upstream), and the other standing wave is observed away from the jet whose wavelength is the difference between the wavelength of the screech and the wavelength of the standing wave close to the jet.

Even though some aspects of the effect of an upstream reflector are reported in the literature, the problem needs to be investigated deeply to get a thorough understanding of the phenomenon. With this in mind, the effect of an upstream reflector on a circular underexpanded sonic jet screech mode, screech wavelength and amplitude has been investigated in the present study.

II. Experimental Details

A. Jet Flow Facility

The experiments were conducted in the freejet facility at IIT Kanpur. Compressed dry air was stored up to a maximum pressure of

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1.5 MPa in three storage tanks. The compressed air to the settling chamber was supplied continuously from the storage tanks through a control valve. To reduce the flow disturbance caused by the control valve, the settling chamber was kept 2 m downstream of the control valve. The flow was conditioned by two wire mesh screens before entering into the stagnation chamber. A 25 mm diameter tube of length 0.3 m was connected to the settling chamber. The nozzle was fixed at the end of the tube. The extension tube between the settling chamber and nozzle provided the space required for upstream acoustic measurements.

B. Nozzle and Reflector Details

A convergent nozzle of 10 mm exit diameter was used in the present study. To avoid the convergent angle as a parameter in the jet flow studies, a constant area portion of 15 mm length was added at the end of the convergent nozzle, similar to Powell et al.'s [17] experiment, as shown in Fig. 1. The lip thickness of the nozzle was kept as $0.05D_e$ to reduce the receptivity of the jet flow by edge scattering. Two brass circular reflectors of external diameter $1.8D_e$ and $6.0D_e$ with a thickness of $0.5D_e$ were used in the present study. The reflectors could be moved up to $2.7D_e$ upstream of the nozzle exit plane. The experiments were conducted for equivalent correctly expanded Mach numbers M_j from 1.1 to 2.0.

C. Acoustic Measurements

Far-field acoustic measurements were carried out using a G.R.A.S. $\frac{1}{8}$ in. pressure microphone. The microphone was placed $30D_e$ upstream of the nozzle exit and positioned at 120 deg to the nozzle axis. To minimize the sound reflections during acoustic measurements, nearby metal surfaces (stagnation chamber flange, microphone mounting, etc.) were covered with polyurethane foam.

The acoustic signals were acquired with a National Instrument's digital data acquisition card (PCI-MIO-16E-1) using the LabVIEW software at a sampling rate of 160 kHz. The acoustic signals were segmented into 40 blocks with 8192 points each and the spectrum for each block was obtained by fast Fourier transform (FFT) with a frequency resolution of 19.5 Hz. The 40 FFTs obtained were averaged to get a statistically reliable narrowband noise spectrum. The microphone was calibrated using a Larson Davis calibrator to obtain the voltage to pascal conversion factor. No correction was made to the acoustic spectrum to compensate for the free field and atmospheric effect.

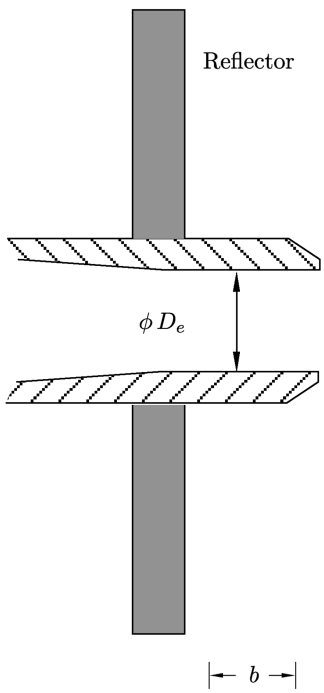

Fig. 1 Schematic diagram of nozzle and reflector.

D. Uncertainty

The stagnation pressure in the stagnation chamber was maintained within an accuracy of ±0.3 kPa. The error in the positioning of the reflector was within ±0.25 mm. The repeatability test of acoustic measurements showed that the frequencies and amplitudes were reproducible within ±39 Hz and ±1 dB, respectively.

III. Experimental Results

A. Effect of Reflector Diameter

The variation of the normalized fundamental screech wavelength λ_s/D_e with correctly expanded jet Mach number M_j for different diameters of the reflector is shown in Fig. 2. Note that the reflector was kept $0.2D_e$ upstream of the nozzle lip, to maintain the actual lip thickness of the nozzle. As the jet Mach number increases, the wavelength of the screech increases until a critical Mach number is reached where a sudden jump in the wavelength occurs. The various modes in the jet screech are labeled as A_1, A_2, B, and C as per the literature (Fig. 2) [14,17]. The commonly observed screech modes in underexpanded sonic jets are axisymmetric modes A_1 and A_2, and helical modes B, C, and D.

For the base configuration (lip thickness was $0.05D_e$), screech exists up to $M_j = 1.41$ only. The addition of $1.8D_e$ and $6.0D_e$ reflectors extend the presence of screech to $M_j = 1.58$ and 1.77, respectively. The modes of the screech are also affected by the size of the reflector. This result is consistent with similar experiments reported in the literature [10].

Receptivity (the process by which external excitation disturbances transfer energy to instabilities in a shear flow) is an important process in the screech feedback cycle. Excitation of a shear layer is due to two primary receptivity mechanisms: direct excitation and edge scattering [18]. The receptivity of the jet can be changed by increasing the nozzle lip thickness or placing a reflector upstream of the nozzle lip. The diameter of the first shock cell in an underexpanded jet increases with increase of jet Mach number. This prevents the acoustic waves, generated by the interaction of the shock wave with the instability wave downstream of the jet (in the third or fourth shock cell), from reaching the nozzle lip. This aerodynamic blockage is the cause for the cessation of screech in underexpanded jets [19]. The reflector, which was kept upstream in the present experiments, is found to reflect the acoustic waves toward the jet shear layer and increase the receptivity of the jet to maintain the screech cycle.

B. Effect of Reflector Position

1. Screech Mode

Figures 2c and 3 show the effect of reflector position (all the results reported hereafter are based on reflector diameter $6.0D_e$) on the screech wavelength. The reflector locations tested were $0.2D_e$, $1.0D_e$, $1.8D_e$, and $2.5D_e$ upstream of the nozzle exit. It is found that the reflector location affects both symmetric (A_1 and A_2) and helical (B, C, and D) modes. For the reflector location $0.2D_e$, modes A_2, B, and C were present. Mode C was absent for the reflector locations $1.0D_e$ and $2.5D_e$. Also, there is no jump in the screech wavelength after $M_j = 1.3$. The reason for the absence of the jump is that mode D is the continuation of mode B [17]. All five screech modes were present for reflector location $1.8D_e$ as seen in Fig. 3b. Thus, the location of the reflector affects the screech wavelength as well as the screech mode.

2. Feedback

To understand the feedback of the screech cycle, experiments were carried out by varying the reflector position, in steps of $0.1D_e$ upstream of the nozzle lip, for a constant jet Mach number. The movement of the reflector and the acquisition of acoustic data was carried out without stopping the jet flow. The advantage of this method is that the stability characteristics of the jet remain constant, so that the only variable is the screech feedback path length. Results of the screech mode studies in the previous section show that the stability characteristics of the jet vary with the jet Mach number. The screech wavelength, when the reflector is at the nozzle exit, was taken as the reference wavelength λ_r for normalization of both screech wavelength (λ_s) and reflector distance from the nozzle exit (b). Note that the reference wavelength is different for different jet Mach numbers.

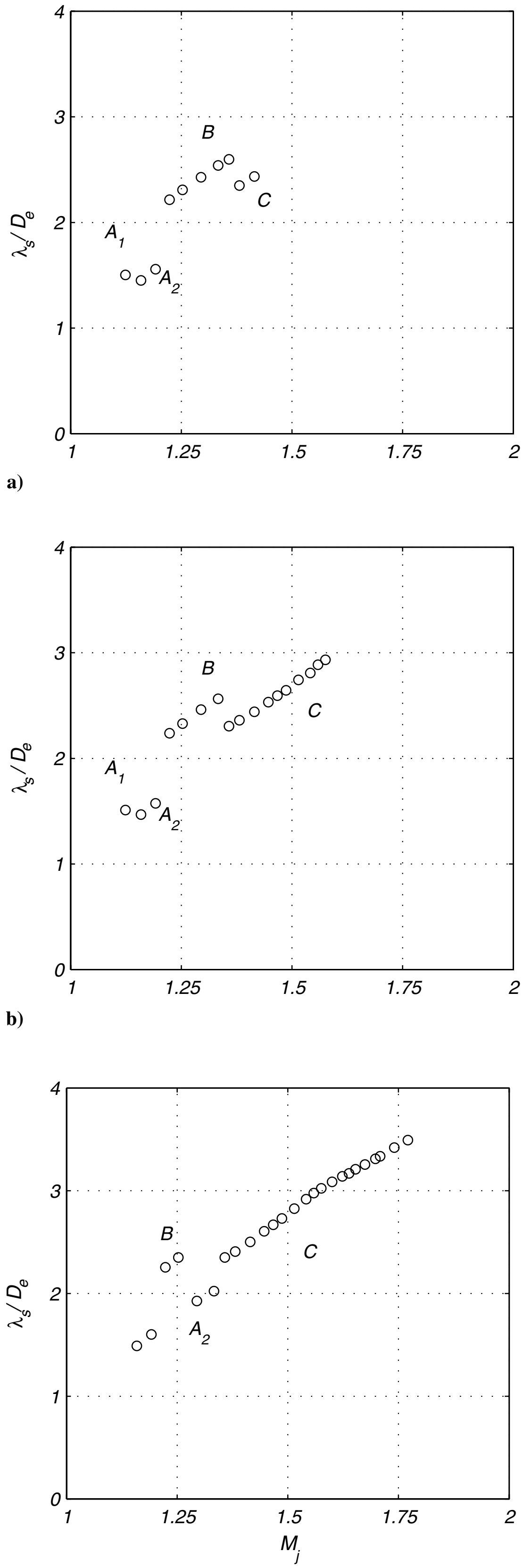

Fig. 2 Screech wavelength of the underexpanded sonic jet with: a) no reflector, b) reflector diameter 1.8D_e, and c) reflector diameter 6.0D_e, at 0.2D_e upstream of nozzle exit.

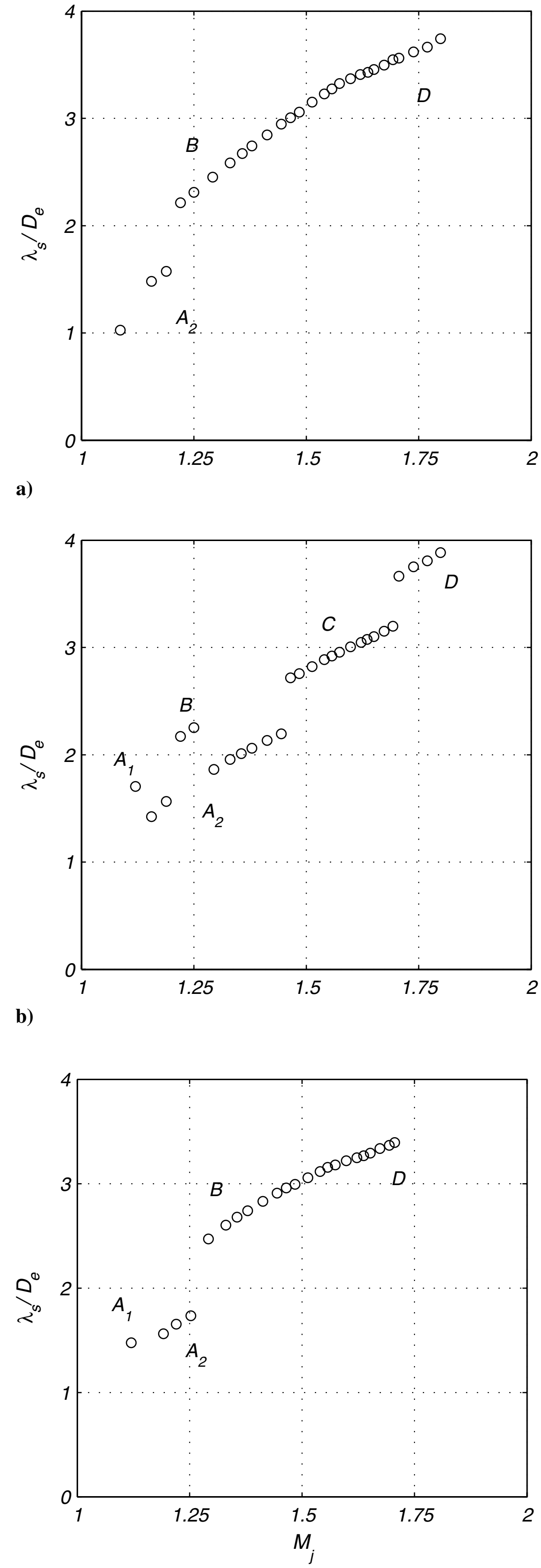

Fig. 3 Screech wavelength of the underexpanded sonic jet for upstream reflector (diameter 6.0D_e) position: a) 1.0D_e, b) 1.8D_e, and c) 2.5D_e.

Figure 4 shows the effect of the reflector position on the wavelength and amplitude of the A_2 screech mode for $M_j = 1.19$. It is seen that the wavelength increases with increase of reflector distance from the nozzle lip up to a certain distance then drops suddenly. When the reflector distance keeps increasing beyond this location, the wavelength increases again. This pattern continued up to the maximum upstream distance $2.7D_e$ tested in the present experiments. This sawtooth pattern is a general characteristic of the feedback phenomenon. The sound generated by the interaction of the shock wave and the instability wave in the jet shear layer propagates upstream and gets reflected by the reflector to form a standing wave with the pressure antinode (maximum pressure) at the reflector surface. This standing wave excites the instability wave in the jet shear layer (receptivity). This instability wave grows in the downstream direction and generates sound by interacting with the shock wave to complete the screech cycle. The wavelength of the standing wave increases with the increase of reflector distance. This excites the higher wavelength of the instability waves to complete the cycle. This continues up to the standing wave wavelength ($\lambda_r/2$). When the reflector is moved beyond that position, the standing wave is able to accommodate one more loop by decreasing the standing wave wavelength to the starting wavelength of the previous loop. That is why the distance between the jump is $\lambda_r/2$, as observed in Fig. 4a.

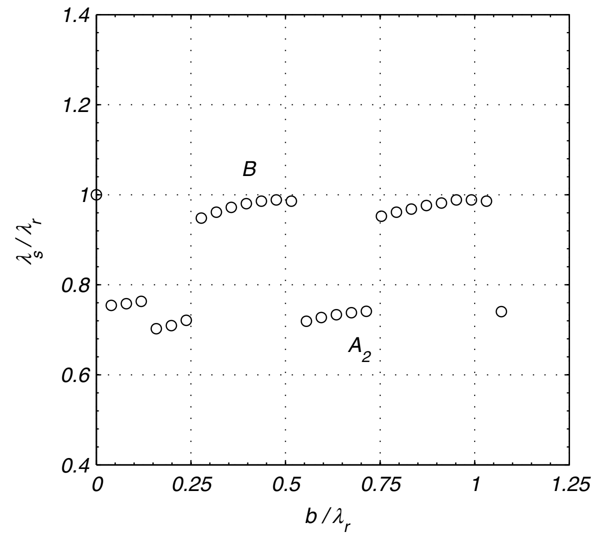

Fig. 5 Effect of reflector (diameter $6.0D_e$) position on screech wavelength for $M_j = 1.29$.

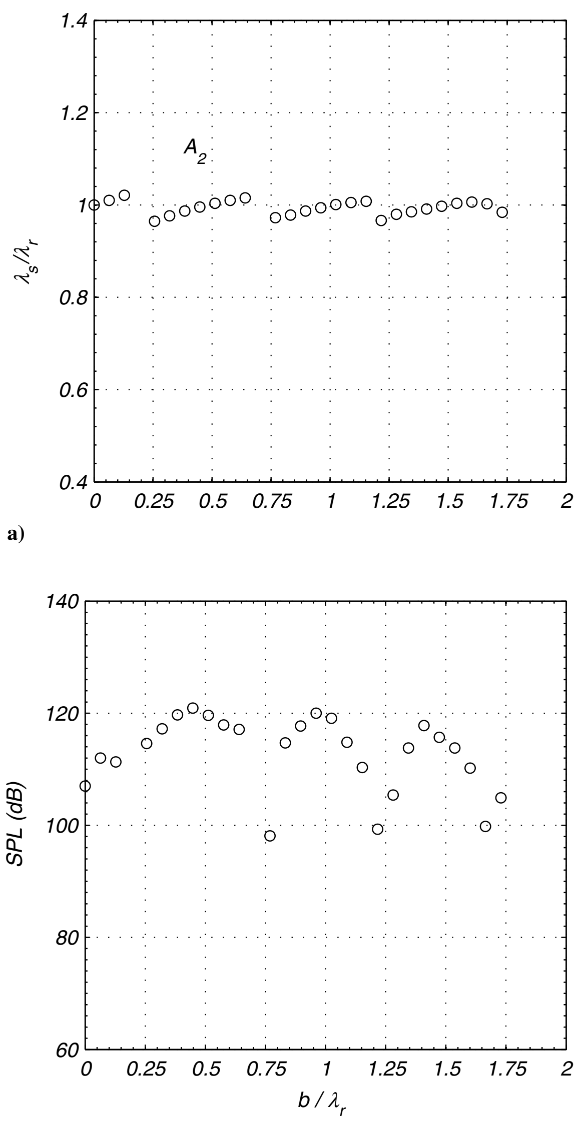

Fig. 4 Effect of reflector (diameter $6.0D_e$) position on: a) screech wavelength, and b) amplitude for $M_j = 1.19$.

The difference between the maximum and minimum wavelengths at this Mach number is 6%.

The amplitude of the screech is proportional to the amplitude of the sound pressure (excitation level) near the nozzle exit. Screech amplitude is maximum when the antinode of the standing wave is near the nozzle exit and minimum when the node is present near the nozzle exit. In Fig. 4b, maximum and minimum screech amplitudes occur at $(n-1)\lambda_r/2$ and $(2n-1)\lambda_r/4$ (where $n = 1, 2, \ldots$), respectively, which correspond to the antinodes and the nodes of the standing wave. The amplitude of the first two points may not be correct because there was a small gap between the nozzle chamfer and the reflector for the first two experimental points.

The effect of the reflector location on the screech wavelength for $M_j = 1.29$ is shown in Fig. 5. Unlike $M_j = 1.19$, (Fig. 4) the change in wavelength is not within a single band but within two bands. The behavior of the screech is different in each band. One is the symmetric A_2 mode and the other is the helical B mode.

The maximum growth rate of the instability wave (most unstable wave) in the jet shear layer is a function of the instability mode and the instability wavelength; that is, if the instability wavelength is fixed, then the maximum growth rate condition dictates the mode of the instability wave. The wavelength of the standing wave increases as the reflector moves upstream, which in turn excites the higher wavelength of instability wave in the jet shear layer. If the growth rate of that instability wave is not sufficient to support the feedback screech cycle (even by adding one more loop in the standing wave) then some other wavelength of the instability wave of a different mode, which has a higher growth rate to support the feedback cycle, is excited. The ratio of the average screech wavelengths of mode B and mode A_2 is $4/3$. This means that the standing wave wavelength of mode B is 1.33 times higher than the mode A_2 for the same reflector position. The difference in wavelength at this Mach number is as high as 30%. This kind of change in screech mode is responsible for the unexplained frequency difference observed in previous studies [15]. The periodicity between the B modes as well as between the A_2 modes is $\lambda_r/2$. This once again confirms that the standing wave is responsible for this mode change. This gives the proof for Tam's weakest link theory that the feedback dictates the wavelength of the screech [1,2].

Unlike the $M_j = 1.19$, no trend in amplitude is observed for higher Mach numbers (not shown). Effective screech tone cancellation/suppression is possible only when the reflector has effective diameter (reflector outer diameter minus nozzle outer diameter) greater than the screech wavelength λ_s [15]. In the present study this condition is satisfied only for $M_j = 1.19$. The current results show that this condition is not applicable to control the screech mode and screech

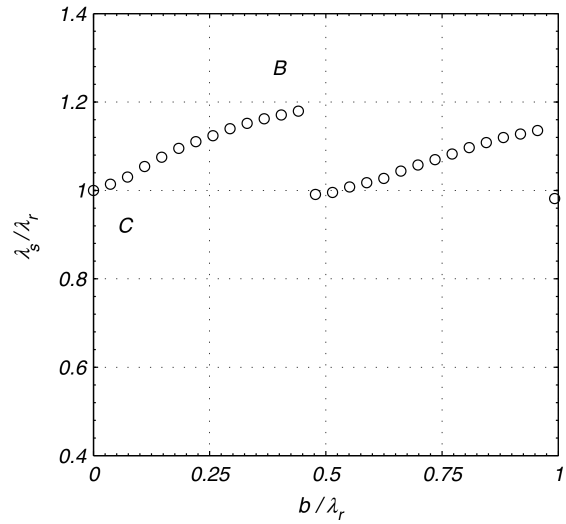

Fig. 6 Effect of reflector (diameter $6.0D_e$) position on screech wavelength for $M_j = 1.51$.

wavelength. Further study is required to find the minimum reflector diameter required to control the frequency of screech.

Figure 6 shows the effect of reflector position on screech wavelength for $M_j = 1.51$. There are two modes of screech (helical B and C) for this Mach number. Even though there are two modes for this Mach number, the change from mode B to mode C is continuous because the difference between the wavelengths of these modes is small. Again the periodicity between the jumps in the sawtooth pattern is $\lambda_r/2$. The jet is only moderately underexpanded in all the cases discussed above. The effect of reflector position for $M_j = 1.71$ (highly underexpanded) is shown in Fig. 7. The qualitative behavior and the distance between the jumps in the sawtooth pattern for $M_j = 1.71$ is the same as the moderately underexpanded jet (Fig. 6).

C. Scaling

The frequency (wavelength) or Strouhal number of the screech is found to decrease (increase) with increasing jet Mach number. In this case there is a possibility that the product of Strouhal number and Mach number may be constant. The Helmholtz number is defined as the ratio of a given frequency to the characteristic frequency (a_j/D_j) of a jet and can be expressed as the product of Strouhal number and Mach number as

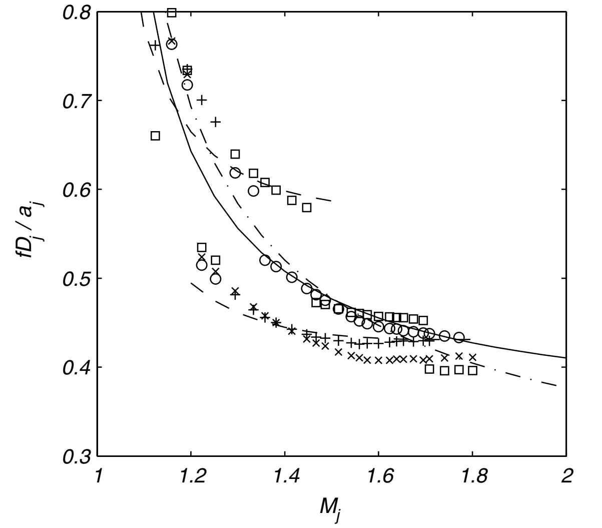

Fig. 8 Effect of reflector (diameter $6.0D_e$) position on screech Helmholtz number: ∘, $b/D_e = 0.2$; ×, $b/D_e = 1.0$; □, $b/D_e = 1.8$; and +, $b/D_e = 2.5$. Comparison with screech prediction formula ——, Tam [2]; -·-·-·, Powell [3]; and – – –, Massey and Ahuja [21].

$$H_j = \frac{fD_j}{a_j} = St_j \times M_j \tag{1}$$

where f, D_j, and a_j are screech frequency, correctly expanded jet diameter, and speed of sound in the correctly expanded jet, respectively. The correctly expanded jet diameter was calculated using momentum conservation [20].

A plot of Helmholtz number H_j with jet Mach number for all the reflector locations of the present study is shown in Fig. 8. The available theoretical (Tam [2] and Powell [3]) and empirical (Massey and Ahuja's helical mode [21]) formulas for screech frequencies (converted to screech Helmholtz number) are also shown in Fig. 8. It is found that the Helmholtz number is asymptotically approaching a constant for $M_j > 1.55$, for all reflector locations irrespective of the screech mode. But the value of the constant is different for different reflector locations. The specialty of this $M_j = 1.55$ is that in an underexpanded sonic round jet, the Mach disk occurs in the jet shock cell structure approximately at this Mach number. The empirical formula given by Massey and Ahuja for the helical mode also shows the constant scaling in Helmholtz number above $M_j = 1.55$. The

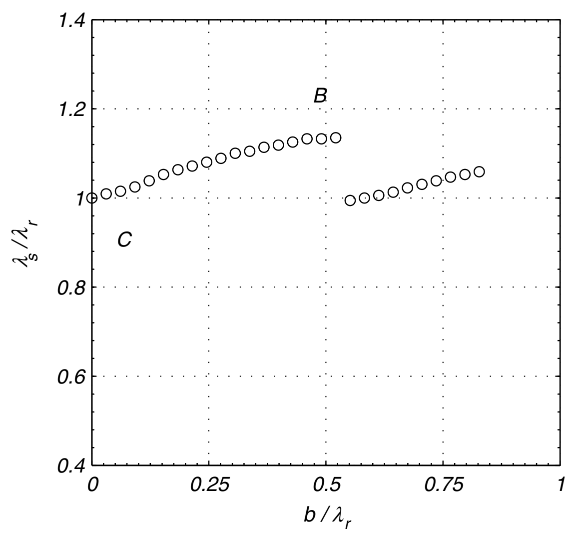

Fig. 7 Effect of reflector (diameter $6.0D_e$) position on screech wavelength for $M_j = 1.71$.

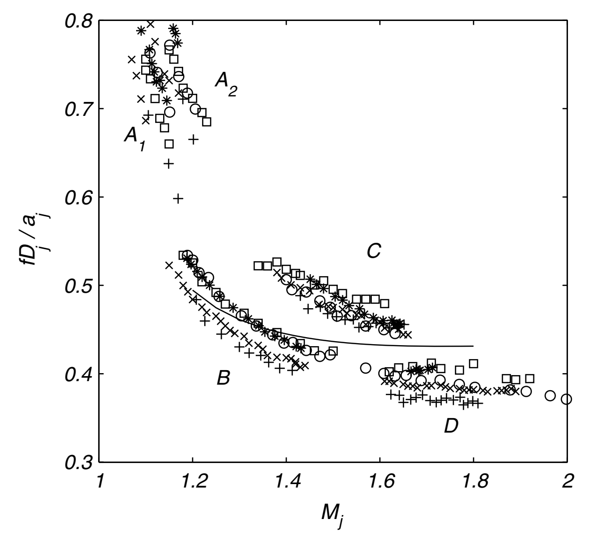

Fig. 9 Comparison of screech Helmholtz number of underexpanded sonic jet: *: Davis and Oldfield [7], ×: Ponton and Seiner [10], +: Powell et al. [17], ∘: Norum and Shearin [22], □: Panda et al. [23], and ——: Massey and Ahuja [21] (helical mode).

Table 1 Average screech Helmholtz number of highly underexpanded sonic jets reported in the literature

Authors	Mode C	Mode D
Davis and Oldfield [7]	0.460	0.404
Ponton and Seiner [10]	0.454	0.386
Powell et al. [17]	0.454	0.371
Norum and Shearin [22]	0.450	0.392
Panda et al. [23]	0.483	0.403

models of Tam [2] and Powell [3] cannot predict this because these models are valid for moderately expanded Mach number only (i.e., before the formation of Mach disk in the jet structure).

The constant scaling of screech Helmholtz number for highly underexpanded jets encouraged us to look into the experimental screech data in the literature. The experimental data in the literature ([7,10,17,21–23]also shows that the Helmholtz number is constant for $M_j > 1.55$, but the value of the constant is different for different screech modes (Fig. 9). The compiled values of average screech Helmholtz number for $M_j > 1.55$ from the literature show that the values of the constant are 0.45 and 0.40 for mode C and mode D, respectively, (Table 1). Massey and Ahuja [21] gave a single formula for all the helical modes (mode B, C and D), so the formula gives the average frequency ($H_j \approx 0.43$) of mode C and D for $M_j > 1.5$ (Fig. 9). Morrison and McLaughlin [24] reported that the most dominant instability wave for low Reynolds number subsonic and perfectly expanded supersonic jets from $M_j = 0.9$ to 2.5 is $H_j \approx 0.4$. This shows plausibly that there might be a similarity between the dominant instability waves of highly underexpanded jets and perfectly expanded jets.

At present there is no theoretical formula to predict the screech frequency for highly underexpanded jets (after the formation of Mach disk in the jet structure). Any new theoretical model for screech should take this Helmholtz number scaling constant into consideration.

IV. Conclusions

The placement of a reflector upstream of a nozzle exit produced a standing wave by reflecting the upstream propagating sound, which is generated by the interaction of a shock wave with an instability wave in the jet shear layer. The location of the reflector affects the standing wave wavelength, which in turn affects the excitation (receptivity) of the jet shear layer to control the screech mode, screech wavelength, and its amplitude. This explains the reason for the scattering of the screech wavelength and the amplitude reported in the literature. The reflection of the acoustic wave depends on the diameter of the reflector, which in turn controls the existence of the screech. The jet without reflector supports screech up to $M_j = 1.41$ only. The reflector of diameter $6.0D_e$ upstream $0.2D_e$ of the nozzle exit maintains screech up to $M_j = 1.77$.

The present results show that a jet can sustain more than one mode of screech (symmetric and helical or both helical) at a particular Mach number depending on the standing wave (excitation) wavelength. Variation of the screech wavelength λ_s with the reflector distance shows the typical sawtooth pattern. In the case of the single mode, the period between the jumps in the sawtooth pattern is the standing wave wavelength $\lambda_r/2$. When two modes exist, the interval of repetition of a particular mode is the wavelength of the standing wave. The maximum difference in the wavelength is around 6% in the case of single mode and 30% in the case of two modes. The effect of upstream reflector position on both moderately underexpanded jet and highly underexpanded jet screech shows similar behavior.

The screech Helmholtz number has a constant value for highly underexpanded sonic round jets (after the formation of Mach disk in the jet structure), but this constant depends on the screech mode. From the available experimental screech data, this constant is found to be approximately 0.45 for mode C ($H_j \approx 0.45$) and 0.40 for mode D ($H_j \approx 0.40$). This screech Helmholtz number scaling constant is important for screech frequency prediction because at present there is no theoretical formula available for prediction.

References

[1] Tam, C. K. W., "Jet Noise Generated by Large Scale Coherent Motion," *Aeroacoustic of Flight Vehicles: Theory and Practice*, edited by H. H. Hubbard, Vol. 1, of NASA RP-1258, 1991, pp. 311–390.

[2] Tam, C. K. W., "Supersonic Jet Noise," *Annual Review of Fluid Mechanics*, Vol. 27, 1995, pp. 17–43. doi:10.1146/annurev.fl.27.010195.000313

[3] Powell, A., "On the Mechanism of Choked Jet Noise," *Proceedings of the Physical Society, London, Section B*, Vol. 66, No. 12, 1953, pp. 1039–1056. doi:10.1088/0370-1301/66/12/306

[4] Raman, G., "Advances in Understanding Supersonic Jet Screech: Review and Perspective," *Progress in Aerospace Sciences*, Vol. 34, Nos. 1–2, 1998, pp. 45–104. doi:10.1016/S0376-0421(98)00002-5

[5] Raman, G., "Supersonic Jet Screech: Half-Century from Powell to Present," *Journal of Sound and Vibration*, Vol. 225, No. 3, 1999, pp. 543–571. doi:10.1006/jsvi.1999.2181

[6] Raman, G., Panda, J., and Zaman, K. B. M. Q., "Feedback and Receptivity During Jet Screech: Influence of an Upstream Reflector," AIAA Paper 97-0144, 1997.

[7] Davis, M. G., and Oldfield, D. E. S., "Tones from a Choked Axisymmetric Jet. I. Cell Structure, Eddy Velocity and Source Locations and II. The Self Excited Loop and Mode of Oscillation," *Acustica*, Vol. 12, No. 4, 1962, pp. 257–277.

[8] Harper–Bourne, M., and Fisher, M. J., "The Noise from Shock Waves in Supersonic Jets," AGARD CP-131, 1973.

[9] Poldervaart, L. J., Wijnands, A. P. J., and Bronkhurst, L., "Aerosonic Games with the Aid of Control Elements and Externally Generated Pulses," AGARD CP-131, 1973.

[10] Ponton, M. K., and Seiner, J. M., "The Effects of Nozzle Exit Lip Thickness on Plume Resonance," *Journal of Sound and Vibration*, Vol. 154, No. 3, 1992, pp. 531–541. doi:10.1016/0022-460X(92)90784-U

[11] Kweon, Y.-H., Miyazato, Y., Aoki, T., Kim, H.-D., and Setoguchi, T., "Experimental Investigation of Nozzle Exit Reflector Effect on Supersonic Jet," *Shock Waves*, Vol. 15, Nos. 3–4, 2006, pp. 229–239. doi:10.1007/s00193-006-0021-6

[12] Westley, R., and Woolley, J. H., "An Investigation of the Near Noise Fields of a Choked Axisymmetric Air Jet," *Aerodynamic Noise: Proceedings of AFOSR-UTIAS Symposium*, Univ. of Toronto, Toronto, May 1968, pp. 147–167.

[13] Panda, J., "An Experimental Investigation of Screech Noise Generation," *Journal of Fluid Mechanics*, Vol. 378, No. , 1999, pp. 71–96. doi:10.1017/S0022112098003383

[14] Norum, T. D., "Screech Suppression in Supersonic Jets," *AIAA Journal*, Vol. 21, No. 2, 1983, pp. 235–240. doi:10.2514/3.8059

[15] Nagel, R. T., Denham, J. W., and Papathanasiou, A. G., "Supersonic Jet Screech Tone Cancellation," *AIAA Journal*, Vol. 21, No. 5, 1983, pp. 1541–1545. doi:10.2514/3.60153

[16] Nakazono, Y., Sonoda, Y., Ouchi, Y., and Nasu, Y., "Near-Field Acoustic Characteristics of Screech Jet Exhausted from a Nozzle with a Hard Reflecting Plate," *Journal of Visualization*, Vol. 11, No. 2, 2008, pp. 153–162. doi:10.1007/BF03181930

[17] Powell, A., Umeda, Y., and Ishii, R., "Observations of the Oscillation Modes of Choked Circular Jets," *Journal of the Acoustical Society of America*, Vol. 92, No. 5, 1992, pp. 2823–2836. doi:10.1121/1.404398

[18] Barone, M., and Lele, S., "Receptivity of the Compressible Mixing Layer," *Journal of Fluid Mechanics*, Vol. 540, 2005, pp. 301–335. doi:10.1017/S0022112005005884

[19] Raman, G., "Cessation of Screech in Underexpanded Jets," *Journal of Fluid Mechanics*, Vol. 336, No. , 1997, pp. 69–90. doi:10.1017/S002211209600451X

[20] Tam, C. K. W., and Tanna, H. K., "Shock Associated Noise of Supersonic Jets from Convergent-Divergent Nozzles," *Journal of Sound and Vibration*, Vol. 81, No. 3, 1982, pp. 337–358. doi:10.1016/0022-460X(82)90244-9

[21] Massey, K. C., and Ahuja, K. K., "Screech Frequency Prediction in Light of Mode Detection and Convection Speed Measurements for Heated Jets," AIAA Paper 97-1625, 1992.
[22] Norum, T. D., and Shearin, J. C., "Effects of Simulated Flight on the Structure and Noise of Underexpanded Jets," NASA Tech. Rept. TP-2308, 1984.
[23] Panda, J., Raman, G., and Zaman, K., "Underexpanded Screeching Jets from Circular, Rectangular, and Elliptic Nozzles," AIAA Paper 97-1623, 1997.
[24] Morrison, G. L., and McLaughlin, D. K., "Instability Process in Low Reynolds Number Supersonic Jets," *AIAA Journal*, Vol. 18, No. 7, 1980, pp. 793–800.
doi:10.2514/3.7688

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